Technical Paper for Team ENSCO
DARPA Grand Challenge

Introduction

Team ENSCO will be entering the DARPA Grand Challenge with a modified Honda Rincon ATV. The design utilizes standard off-the-shelf sensors and hardware. The software integrates the sensors with the control hardware. This project is sponsored by ENSCO Inc, a privately owned engineering company that specializes in signal processing and data acquisition. The Team received funding (October 2003) and has initiated the design and construction of the vehicle. Therefore, this paper will describe the overall approach as of the date of the paper. This is the technical addendum to our original technical paper. Changes in design and performance are highlighted to inform DARPA of any significant changes.

Background

Team ENSCO is a group of highly qualified engineers that specialize in the development of innovative technologies. The group is employed and sponsored by ENSCO, Inc., which provides engineering, science and advanced technology solutions for the defense, security, transportation, environment, aerospace, and intelligent automation industries. Founded in 1969, ENSCO is an $85 million, approximately 700-person privately-owned corporation headquartered in Springfield, Va. From signal processing algorithms that make international treaty monitoring efforts more effective, to railroad track monitoring equipment that makes train travel safer, we support government and industry organizations with a variety of solutions that make the world a better place. Our work includes designing sophisticated computer models that make NASA launches more reliable; developing monitoring systems that safeguard government facilities and national landmarks; providing safety assurance and operational efficiency for the FRA and rail industry; and providing mission-critical software development and engineering systems for avionics operations and control.

Team ENSCO will incorporate a series of innovative guidance and vision technologies on a lightweight highly flexible all-terrain vehicle to meet the Grand Challenge. The vehicle will travel at speeds up to 68 mph over rough terrain being guided by a custom navigation system combined with DGPS technologies. Obstacle avoidance will be achieved using LIDAR, Doppler Radar, and Stereo Vision Camera systems. Team ENSCO accepts this challenge and believes that our unique experiences and innovative skill set will assure a competitive vehicle for this major event.

System Description

Mobility

This vehicle frame is a stock Honda Rincon 4 wheel drive all terrain vehicle (ATV). Picture of the proposed vehicle is shown in Figure 1. Substantial changes to the body will be made to enclose the electronics and provide protection to the suspension and sensors.. The fundamental mechanical components of the steering and braking systems are what are available with the stock Rincon ATV. The wheels spacers are aftermarket which makes the track larger than stock. The power of the internal combustion engine is transmitted through the stock transmission. The vehicle has two wheel steering and four wheel drive. Figure 2 gives the vehicle ground contact layout with dimensions.

The steering is controlled with a DC brushless servomotor mounted to the stock steering shaft. The emergency brake is spring-loaded for failsafe operation. Two independent braking circuits are used, hydraulic and cable, to assure braking if one circuit completely fails. A detailed description of the braking system is in the ESTOP section of the paper. When power-off is commanded or the external safety switch is thrown, the brakes are fully applied and the computer controls the steering and engine states. The gearshift is controlled with electrical relays using the stock circuitry and hardware. The throttle is a servo actuator.

Under normal braking or acceleration the computer controls the states of the brake, throttle, and steering actuators.

Power

The stock 649cc single cylinder four-stroke engine running with high-octane pump fuel will supply the power. The engine power will be approximately 24.5 ±2 kilowatts. The engine will supply all the power. A total of sixteen gallons of pump fuel will be carried from the start.

Seven sealed lead acid batteries (20 amp-hr) or equivalent are used to operate the engine starter motor and lights when the engine is not running, and the steering, throttle and the choke when the engine is running. The batteries are a sealed lead-acid or equivalent to prevent spilling in case of rollover.

Processing

Three computers have been implemented One computer handles the environment sensing, while the second computer handles the map matching and path logic, and the third computer handles vehicle control and system feedback. Two of the computers are 1.6 GHzGETAC Laptops with custom power, data acquisition cards, and filters. The control computer consists of a 1.3 GHz processor running a real-time operating system, as well as a motor controller and digital and analog interface cards. This computer is a PXI (PCI extensions for Instrumentation) form factor. Figure 3 shows system architecture with logic flow.

Classification of objects

A three-level scheme for classifying objects will be implemented. The highest level will consist of map data and DARPA route constraints. The map data will be processed prior to the race to determine zones that will exceed safe operating parameters of the vehicle. These and the limits of the route width defined by DARPA will be considered as hard lateral limits.

The on-board sensors will be used to detect and classify objects in real time. Sensor fusion will be used to assist in correctly classifying objects as hard, to be avoided; medium, vehicle can move over the object but will have to reduce speed; or soft, object can be traversed without reduction in commanded speed. Other challenge vehicles detected and identified by the sensor suite will be considered hard objects to avoid collisions.

Reactive Route Planning

Reactive Route Planning will be accomplished dynamically from all available localization and obstacle data by placing intermediate waypoints between DARPA defined route waypoints that the Challenge vehicle must also pass through. These intermediate waypoints will be strategically placed to keep the vehicle away from all known detected and classified obstacles stored in the local area map database. The shortterm route-planning algorithm will dynamically select a route within boundary constraints that avoids all hard objects and stays within route boundaries while providing the fastest path to the next route waypoint. Each leg of this route will also be associated with a speed limit that the vehicle must not exceed based on the classification of the objects it chooses to traverse as well as the DARPA-supplied speed limits. Further vehicle speed and steering manipulation will be done as necessary while driving to prevent vehicle instability.

Vehicle Control

The vehicle will be controlled by commanding throttle, brake, and steering with a realtime feedback loop in order to follow the short-term route over the intermediate waypoints. Speed for each segment between intermediate waypoints will be selected by reference to the obstacle class for that segment. Throttle, brake, and steering commands may be further modified by feedback from vehicle accelerations and rates obtained from the navigation system state vector in order to maintain vehicle parameters within safe limits. Steering inputs will be applied to null out errors in the vehicle path from the short-term route. Steering input limits, both magnitude and rate of change, will be a function of vehicle speed and acceleration. A mechanical system for righting the vehicle if overturned will not be included in the design.

Internal Databases

The Challenge Vehicle will store on the onboard computers two types of data: preprocessed and dynamically derived data. Pre-processed data consists of map data, boundaries, hydrology, and elevations. Dynamically derived data consists of sensor data, object detection data, and classification data.

Map data will be acquired from the USGS for the southern California and Nevada regions. These maps will consist of 1:24,000 scale DEMs (Digital Elevation Models) and DLGs (Digital Line Graphs). The accuracy of these maps is 40 ft. These digital maps will be analyzed with commercial and custom developed software to determine zones that the vehicle will not be able to traverse due to steep slopes, deep water, etc. Road, bridge, and stream locations will also be stored for use in path planning and object detection and classification while the vehicle is in motion. All map data will be pre-stored on the vehicle for two purposes: high risk long distance route planning once the GPS waypoints are given to us and predictive information during dynamic operation. For instance, if it is known that a stream is within a certain 40ft region then the software interpreting the sensor data will place a higher likelihood on the determination of finding water in the region and the object will be correctly detected and classified according to known depth from the pre-stored map data. However, due to the inaccuracies of the map data, the sensor data and GPS data will be the sole information used to calculate the immediate movements of the vehicle.

Other data stored on the Challenge Vehicle consists of raw sensor data from each of the sensors and processed sensor data for the entire path of the vehicle. All sensors will be recorded including environment, state, and localization sensors with the exception of the stereo-vision camera. This is due to the sheer volume of memory needed to record the image data. The stored processed data includes the planned path and all identified objects along with object characterizations such as maximum speed the object can be traversed, the location of the object, the size of the object, etc.

Environmental Sensing

The environmental sensing system uses a combination of sensors that input data into the database. The primary sensors are one LIDAR systems, 3 doppler radars, and a stereo camera system. Figure 1 shows the approximate location of the sensors. The LIDAR and stereo vision sensors identify immediate terrain with a high degree of resolution and their data is used to locate obstacles. The Doppler radars are used to provide an independent measurement of longitudinal and lateral velocities.

The raw inputs from the LIDAR and stereo camera systems will be used to construct a local map of the terrain in front of the vehicle. The LIDAR system directly gives range measurements from its point of attachment to points on objects in front of the vehicle. Knowledge of the beam direction plus the location and orientation of the vehicle at the time of measurement will be used to update the environment map once per measurement. The stereo camera requires a significantly more complex algorithm than the LIDAR before its raw input can be used to update the environment map. Team ENSCO will use a previously proven software package in order to achieve a high quality mapping between the stereo images and distances to points within the field of view. The Team will purchase and use an implementation of SRI's Small Vision System (SVS) software that comes standard with certain brands of stereo vision hardware.

Used previously as part of DARPA's Tactical Mobile Robotics initiative, the SVS includes SRI's patent pending Stereo Engine algorithm, which consists of 5 stages: Rectification, Feature Extraction, Correlation, Filtering, and 3D reconstruction. Thus, lens distortion is removed, and the correlation between the Laplacian of Gaussian of each image is used to find disparities between the images, matches with high probabilities are selected, and a cloud of 3D surface points in front of the vehicle is produced and becomes accessible by ENSCO's custom software.

ENSCO's custom software utilizes the stereo camera system three-dimensional space point cloud and the LIDAR 2-D point cloud. The total volume in front of the vehicle is broken down into a number of 2-D elements 41,000 square meters. When points from the stereo camera image and LIDAR are detected within these volumes, control logic uses a vehicle model and the environmental map to classify and characterize obstacles. Some of the defining features are based on size, type, location, and maximum speed they can be traversed. The software then stores this information into the onboard databases for use by the navigation logic. If the obstacle is determined to be above the ground clearance of the vehicle, commands are generated to instruct the path planner arbitrator (navigator) to avoid the obstacle.

There are three fundamental zones of interest in front of our vehicle, long range, short range, and instantaneous. A simplified schematic of the controls is shown in Figure 3. Each of these zones is covered by the set of sensors shown in Table 1.

Sensor	Region			Active/	Horizon
	Instantaneous	Short Range	Long Range	Passive	
	X < 25 ft	25 ft< X <200 ft	200 ft > X		
Stereo Camera	X	X		P	300 ft
Lidar	X	X		A	100 ft
DGPS		X	X	P	N/A
Doppler Radar	X	X		A	1000 ft
Map Data			X	P	N/A
Magnetic Compass		X	X	P	N/A
INS	X	X	X	P	N/A

State Sensing

The vehicle has an inertial navigation system (INS- Inertial Science Inc. RRS75). This device has 3 accelerometers and 3 rate gyros that will provide the control system with information for 6 degrees-of-freedom of the vehicle state. This is integrated into the dead reckoning and the vehicle navigation control system. The purpose of the INS is to determine vehicle stability as well as to assist with determining vehicle position.

There are also sensors to detect if the engine is running, if brakes are applied, if acceleration is applied, and the position of the steering motor. There are also temperature sensors to monitor engine and other critical components.

The stability control system limits the curvature commanded as a function of speed to minimize the risk of vehicle rollover.

Localization

ENSCO has developed a system that uses a commercially available dual frequency (L1/L2) GPS receiver. Anovatel Pro-Pack LB will be used for the challenge vehicle. It is augmented with Differential Global Positioning System (DGPS) receivers to provide corrections when in coverage. Both L-band Omnistar HP and WAAS corrections are used with prefenece set to use Omnistar corrections over WAAS corrections when available. The output of the GPS will be combined with the INS system utilizing a Kalman filtering approach to geolocate the vehicle within the course. This information combined with the three axis doppler radar ground sensor, and magnetic compass to provide very accurate vehicle position location and heading with sub-meter accuracy.

Team ENSCO requests permission to subscribe to a commercially available satellite service from OmniSTAR to interface with the INS system. This system claims position accuracies of .3 meter (¡Ö1.0 ft) or less utilizing the chosen dual frequency DGPS receiver.

The Kalman filter will estimate the states of the vehicle and associated measurement errors. In addition we plan to test for erroneous GPS fix information by comparing the change in GPS position with vehicle speed, heading, and yaw rate from the INS and the magnetic compass prior to introducing each GPS fix into the Kalman filter.

Similar schemes of coupled tactical grade INS / GPS systems[1] show that during full GPS outages of 30 seconds, the INS / Kalman filter arrangement is able to keep radial 2-D position difference to less than 1 meter.

Figure 5. shows that Team ENSCO's vehicle can navigate within the 10 ft boundary with DGPS alone if the signal is available and with multi sensor fusion in the INS without DGPS. Where there are true hard boundaries such as tunnels, the Doppler radar and LIDAR system will be capable of centering the vehicle within the boundary.

The route boundaries will be considered hard obstacles that must be avoided. They are input to the reactive route planning algorithm as described in the processing section.

Communications

The vehicle is designed to be independent with no external communication.

As with all GPS systems, the DGPS system will be receiving wireless signals from the GPS satellites. The differential correction will be acquired using commercially available OmniSTAR and the public signals from Wide Area Augmentation System (WAAS) and the National Differential GPS transmitters (NDGPS).

Autonomous Servicing

There will be no autonomous servicing of this vehicle. The vehicle will go to the designated checkpoint, wait the required time, and then proceed to the next waypoint.

Non-Autonomous Control

A joy-stick controls will be attached to the vehicle for non-autonomous control. It will be designed to allow movement of the vehicle at walking speed. When joystick is centered the vehicle is stopped and the brakes will be fully applied.

System Performance

Previous Testing

No testing has been done on the assembled vehicle. Individual sensors have been tested and evaluated to determine if they will perform the require functions. These sensors

[1] Scherzinger, B.M. "Robust Inertially-Aided RTK Position Measurement" www.applanix.com

include; the dual frequency DGPS and Kalman filter integrated with the INS module built on the PC104 computer stack. The results of these tests are presented in the localization section of the paper. The Doppler radar has been successfully tested and meets the design requirements. Modifications of the tested system will be done to meet the final configuration presented in this paper. The other sensors are on order and will be tested upon arrival.

Planned Testing

The vehicle will be tested in three stages. The first stage is in the lab to assure that the control systems are functioning as designed. The second stage is in the company parking lot to determine the performance of the path logic and waypoint guidance. The third is on a local ATV/Motorcycle trail to detect the performance of the system under high speed rough terrain operation. In each case the specific parameters will be monitored and evaluated. The system will be designed to operate under water up to 5 ft deep.

First Stage

The first series of tests are to evaluate the overall control system characteristics. The mechanics of the braking, steering, engine starting and stopping, throttle control, and other safety equipment will be evaluated. The vehicle will be mounted on a stand while all these tests are completed. The braking system will be tested to evaluate the brake activation and braking rate control. Emergency mechanical brake and the E-STOP actuation and control will also be tested.

The throttle will be tested to evaluate idle control, high revolution limiter, cruise control logic. The steering system will be tested for the steering range, steering rate control and speed dependence.

All the sensors will be installed and calibrated while mounted on an additional ATV vehicle operated by a human driver. The DGPS and navigation system will also be installed. A series of tests running on a local ATV trail will be operated to evaluate the sensors and data acquisition systems. This test will determine if additional sensors are needed or a replacement sensor is required. Upon completion of this test, the sensors will be transferred to the competition ATV.

Second Stage

The second stage will be in the company parking lot to determine the performance of the emergency braking, rollover protection and correction, and all the safety components of the system.

1. The first test will be to evaluate the vehicle braking capability. Defined courses will be setup using highway cones in the company parking lot. The path of travel will be tightly defined using single foot waypoints for the vehicle. The only obstacle avoidance algorithms will be the forward acting Doppler radar. The E

STOP functions will tested at this point. Any further testing will be dependant on successful completing the previous tests.
2. The next test will be to drive the vehicle at stationary barriers using the forward facing Doppler to apply the brakes and stop before impact. A series of speeds will be conducted to assure safety up to the fastest speed of the vehicle.
3. A slalom course and skid pad will be setup in the parking lot using highway cones. The path will be defined using tightly spaced DGPS waypoints. Testing will be conducted at varying speeds. The goal is to bring the vehicle to its limits for rollover and sliding out. Outriggers will be used during this test to prevent damage to the vehicle. These limits will be used in the control logic to minimize the risk of this happening on the course. Near rollover recovery logic will be implemented at this time.
4.
5. No deepwater testing was conducted. Team ENSCO is designing the system to pass through 5 ft of water. All obstacle avoidance systems will become ineffective while under water. Only navigation using dead-reckoning will be done underwater.
6. Obstacle avoidance will be tested at this time. The following conditions will be tested; curb approach, in-tunnel centering, fence detection, high obstacle detection, and hole detection.

Third Stage

Arrangements have been made to utilize a local ATV/Motorcycle trail to detect the performance of the system under high speed rough terrain operation. Again, a series of tests will be conducted on the ATV trail.

1. The first test on the trail will be conducted using previously recorded highly accurate DGPS waypoints at one-foot intervals. This will be collected with another ATV driven by a driver. The purpose of this is to evaluate the driving and control systems. Many runs will be conducted at varying speeds to assure that the throttle, steering and braking controls are functioning properly. The upper dynamic limits will be defined using this test series. During these tests the obstacle avoidance systems will be operating, however, the control functions will be disabled so an evaluation of what the control system will produce under actual conditions. The control system will be modified if necessary to correct erroneous commands that would of been given to the control module. Once the team is satisfied with the results the control system will be activated.
2. The second test will consist of removing groupings of DGPS coordinates from the input file so the path finding and obstacle avoidance control logic will have to navigate through the missing zones. Different speed criteria will be used for the chosen test zones of the trail. Many repeat runs will be conducted. This will demonstrate that path finding and obstacle avoidance works for varying speeds.
3. Continuing on the third test we will remove many more groups of waypoints in the more difficult parts of the course. All components will be functioning. The

overall performance of the complete system will be evaluated and modified if necessary.
4. The next test will be conducted on the same site but using an input file generated through DARPA. The full database implementation and varying speed limits will be conducted. In addition, intermittent sensor failure of DGPS will be simulated.
5. The final test will utilize a second test site and a DARPA formatted file to simulate the actual race. Additional moving ATV vehicles will be operating on the site to simulate the other autonomous vehicles. The performance of the vehicle on this course will highlight the areas of improvement needed. A cycle of testing and modification will be conducted as time permits. Upon successful completion of these tests, Team ENSCO would consider the vehicle ready for the race.

Safety and Environmental Impact

The top speed of the vehicle is 68±5 mph. The vehicle is estimated to get an average of 16 mpg and the 16 gallons of fuel will provide approximately 2560 miles of total range.

The fuel is contained in two Fuel Safe racing fuel tanks that have bladders to prevent spill an explosion in case of tank punctures. In addition, the tank is guarded with frame supports and skid plates to minimize the risk of tank puncture. The electric fuel pump is directly controlled by the E-Stop Disable relay. Upon activation of the disable relay, the fuel pump is shut down without computer control.

These safety precautions eliminate the need for additional fire suppression systems. No fire extinguisher will be carried on the vehicle. The support crew will have an extinguisher and other first aid and safety equipment when working on the vehicle. The exhaust system will have a factory spark arrestor.

The safety lighting system will consist of a ring of amber LED Flashing lights or white LED's with amber lenses that will continuously scroll around the vehicle near its maximum perimeter. A complete cycle of the lights will circle the vehicle within two seconds.

The alert/siren system will consist of an off the shelf alarm. This will produce an intermittent chirp every 5 seconds with a volume of 112 db at 10 ft.

E-Stops

The E-stop will trigger an electrical relay that will cut the power to the brake deactivator. The spring-loaded brake will apply automatically.
The estimated stopping distance under disable emergency stop at a the top speed of 68 mph is less than 150 ft from signal to final stop with a ground surface that provides a friction coefficient of .5 or greater.

When disable emergency stop is activated, the following procedure will occur:

1. Throttle returns to idle
2. Brakes pump on full
3. Emergency Brake on Full
4. Steering returns to straight position
5. Engine full stop
6. Lights off
7. Intermittent sound off
8. Main power disconnect

When normal stop is activated the following procedure will occur:

1. Throttle returns to idle
2. Brakes on controlled stop
3. Emergency brake active
4. Lights on
5. Intermittent sound on
6. Computer remains active

When normal stop is deactivated the following procedure will occur:

1. Brakes are released
2. Throttle is applied
3. Lights remain active
4. Intermittent sound remains active

The manual stop buttons cuts the power to the brake deactivator. The spring-loaded brake will apply automatically. The main power is disconnected and the engine control module is grounded causing the engine to stop completely. This will prevent any unexpected movements.

To move the vehicle, a two locking levers on the outside of the vehicle will release the brakes using the mechanism. The computer control system always returns the transmission to neutral when the vehicle comes to a stop. However, if the computer fails to put the vehicle in neutral, the torque converter clutch allows pushing of the vehicle even if it is stuck in gear.

Radiators

The Team ENSCO Challenge Vehicle will radiate deliberately from obstacle avoidance sensors. These consist of LIDAR and Doppler radar. One SICK model LMS 220-30106 scanning LIDAR will be fitted to the front of the vehicle. Each will scan a 180 deg arc with some overlap at the extended centerline of the vehicle. The lasers maximum range is approximately 150m and meets the following standards:

Wavelength: 905nm
Power: 43.5 mW/(m^2)
Standard: Producer's Declaration for Laser Protection Class 1, 21 CFR 10.40.10 (U.S.A).

The Doppler radar sensors are planned to be DRS 1000 units from GMH engineering. These provide speed sensing. This sensor radiates in the Ku band at 35.5 +/- .1 GHz. The beam diverges at a 6 deg angle from the sensor boresight and radiates at an average RF power of 0.02W and an effective radiated power of 0.98 W. The sensor complies with FCC Part 90, Subpart F regulations.

The ATV exhaust is rated at 96db at 10 ft. Siren sound will produce an intermittent chirp every 5 seconds with a volume of 112 db at 10 ft.

Environmental Impact

1)The Team ENSCO Challenge Vehicle has four properties that which may conceivably cause environmental damage,

• It depends on contact between the wheels and ground to provide locomotion, and will at times travel upwards of 68 miles per hour. However, the control logic of the vehicle is construed to avoid loose surfaces and obstacles, so the vehicle is envisioned to travel over those areas on which it will make the least impact.
• Its primary means of energy generation is an internal combustion engine that will emit exhaust.
• It will carry up to 16 gallons of gasoline. However, as is mentioned previously, we intend to use ATL, Inc. brand non-explosive fuel tanks with bladders; were the Challenge Vehicle to impact a surface while under power, the fuel tank should neither explode nor rupture and leak. Finally, the fuel system will be water-tight in order to prevent leakage while submerged in a body of water.
• The vehicle will have seal lead-acid or equivalent to prevent spilling in case of rollover or impact. The battery is mounted inboard of the frame to prevent impact on objects.

The wheels and propulsion system of the Team ENSCO Challenge Vehicle are nearly unmodified from their original stock configuration, and what small modifications which are present are themselves aftermarket modifications purchased from commercial vendors. We do not imagine that the environmental impact of our Challenge Vehicle should be much different from the original stock vehicle. In fact, money and effort have been exerted specifically to lower the potential for environmental damage from our vehicle.

2) The maximum physical dimensions of our vehicle are...
Length: 86 inches

Width: 54 inches
Height: 60 inches
Weight: 950 pounds

3) Vehicle ground contact Footprint: 44 in^2
Maximum Static Ground Pressure: 21 lb/in^2
Maximum Dynamic Ground Pressure 42 lb/in^2

Conclusions

As presented in this paper, Team ENSCO has dedicated a significant amount of effort to design a vehicle that will meet the DARPA Grand Challenge Rules with a high probability of success. The funding for the project was received and construction has been initiated and completed. The look of the vehicle will be significantly different since a custom ABS plastic body will be made for the ATV frameTeam ENSCO is very excited by this project and will do everything possible to participate professionally and competitively.